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ABSTRACT

Using our extensive data on the reactions $a + p \rightarrow c + x$, where a and c are charged pions or kaons, and where c is in the fragmentation region of a, we have extracted quark structure functions for the pion and kaon within the framework of the recombination model. We obtain $n^{\pi} = 1.0 \pm 0.1$ and $n^{K} = 2.5 \pm 0.6$, where n is the leading $(1-x)$ power of the non-strange valence quark distribution. The non-strange sea quark functions have $n \approx 3.5$ for both the pion and the kaon.

The success of the quark/parton picture in describing the results of both deep-inelastic leptoproduction and large p_T hadronic scattering experiments has prompted attempts to extend the picture to low p_T hadronic processes.[1] The first objective of such a program is to model low p_T scattering in terms of structure functions determined from leptoproduction experiments.[2] If this is accomplished, then it should be possible to use low p_T data to derive structure functions for those hadrons which cannot be used as targets for lepton probes. The quark recombination model of Das and Hwa[3] has been used successfully together with known proton structure functions to describe low p_T proton fragmentation.[4] Here we use this model to study the structure of pions and kaons using data from the Fermilab Single Arm Spectrometer.[5]

The recombination model for the inclusive reaction $a + p \to c + X$ assumes that a quark and an anti-quark from the fragmenting projectile, $\underline{a}$, fuse together to form the outgoing meson, $\underline{c}$. The invariant cross section for this process as a function of Feynman x is then given by[3]

$$x \frac{d\sigma^{a\to c}}{dx} = \sigma^{a}_{inel} \int_0^x \int_0^x F^a(x_1, x_2) R^c(x_1, x_2; x) \frac{dx_1}{x_1} \frac{dx_2}{x_2}, \qquad (1)$$

where $R^c(x_1, x_2; x)$ is the recombination function, namely the probability that a quark q_1 at x_1 and an anti quark $\bar{q}_2$ at x_2 recombine as the valence quarks of meson $\underline{c}$ at x. $F^a(x_1, x_2)$ is the joint structure function for finding q_1 and $\bar{q}_2$ within projectile $\underline{a}$, and is assumed to take the form[3]

$$F^{a}(x_1,x_2) = F^{a}_{q_1}(x_1)F^{a}_{\bar{q}_2}(x_2)\rho^{a}(x_1,x_2). \qquad (2)$$

Here F^{a}_{q} is the structure function for q within a, and ρ is a phase space factor.

When projectile a is a proton, it has been demonstrated that the recombination model fits the inclusive meson spectrum well.[4] These fits have used the valence quark structure functions derived from leptoproduction as input, and have determined the sea quark structure. Repeating these fits, but allowing the data to determine the valence functions as well, we have also obtained results consistent with those from leptoproduction. However, a surprising result of the proton fits is that the valence and sea quarks together appear to carry all the momentum of the fragmenting proton, in contrast to leptoproduction results where neutral gluons carry approximately half of the momentum. It is argued, however, that the long time scale of hadronic fragmentation gives rise to a "turbulent" sea where all gluons have a chance to fluctuate into $q\bar{q}$ pairs which then may recombine to form mesons.[6] The success of the recombination model with proton-driven reactions suggests using it with meson-driven reactions in an attempt to determine the quark structure functions of mesons.

We have made extensive measurements of the inclusive cross section for the reactions $a + p \rightarrow c + x$, where a and c represent all charged combinations of pions, kaons, and protons, and where c is in the fragmentation region of a.[7] The data are in the range $x \geq 0.2$ and $p_T < 1.5$ GeV/c, and have beam momenta of 100 and 175 GeV/c. An important feature of this experiment is the unambiguous identification of pions, kaons, and protons using the eight Cerenkov counters of the Fermilab M6 beam and Single Arm Spectrometer.[5] In this paper we study the nonleading reactions with incident and outgoing pions and kaons.

The data are fully corrected for experimental effects such as decay in flight, absorption in the spectrometer, and Cerenkov inefficiency.[7,8] The overall acceptance varies from 50% for low energy kaons to 95% for high energy pions. The relative systematic uncertainty between the cross sections for different reaction channels is estimated to be 5%, while the uncertainty in the normalization of the data for a single beam charge and energy combination is less than 10%. Although the data are plotted with statistical error bars, a 10% systematic error has been added in quadrature for the fits.

For this analysis the pion and kaon structure functions, F_q^a, are parameterized as follows. The non-strange valence quark distribution is assumed to be[9]

$$V_u^a(x) = b_u^a \sqrt{x}\,(1 - x)^{n_u^a} , \qquad (3)$$

where the superscript $\underline{a}$ denotes π or K. Charge conjugation invariance insures that $V_u^{a^+} = V_{\bar{u}}^{a^-} \equiv V_u^a$. The sea quarks are given by

$$S_q^a(x) = b_q^a(1 - x)^{n_q^a} , \qquad (4)$$

where the subscript $\underline{q}$ is either $\underline{d}$ for non-strange sea quarks or $\underline{s}$ for strange ones. We further assume light quark universality, namely that $S_d^a = S_{\bar{d}}^a = S_u^a = S_{\bar{u}}^a$. This gives a total of six functions with two parameters each to be determined from the data. The functions are paired together according to (2) for six separate reactions $a + p \to c + x$, as shown in Table I. Note that charge conjugation invariance is assumed in this model to hold for $a \to c$ independently of the rest of the reaction.

For the functions R^c and ρ^a in (1) and (2) we use the forms suggested by Hwa.[10] In the case of incident mesons, ρ^a is assumed to be unity. R^c is related to the valence structure function of the outgoing meson:

$$R^c(x_1, x_2; x) = \alpha^c \left(\frac{x_1}{x}\right)^{n_2^c} \left(\frac{x_2}{x}\right)^{n_1^c} \delta\left(\frac{x_1}{x} + \frac{x_2}{x} - 1\right), \tag{5}$$

where the n_i^c are the leading $(1-x)$ powers of the valence structure functions as given in (3). For R^π we have $n_1^\pi = n_2^\pi = n_u^\pi$, while for R^K the power n_u^K refers only to the non-strange valence quark. It is assumed that the $(1-x)$ power for the strange valence quark of the kaon is given by $(m_u/m_s)n_u^K$, where m_u/m_s is the ratio of the u and s quark effective masses and is taken to be 2/3.[11] Finally, the constant α^c is obtained from the normalization condition:[11]

$$\int_0^1 \int_0^1 R^c(x_1, x_2; 1)\, dx_1\, dx_2 = 1, \tag{6}$$

which states that there are exactly two valence quarks in the outgoing meson.

Our data for the six reaction channels listed in Table I have been simultaneously fitted to the formulae outlined in (1)-(5). Assuming scaling and charge conjugation invariance, the data from both 100 and 175 GeV/c incident momenta and with both positive and negative beam are combined in the fit. The p_T range of the data is limited to three x-sweeps centered at $p_T = 0.3, 0.5, 0.75$ GeV/c, over an x-range of $0.3 \lesssim x \lesssim 0.7$ The upper limit on x is imposed to minimize the effects of forward resonance production and triple Regge contributions.[7] The reaction $\pi^{\pm} \to \pi^{\mp}$ includes appreciable resonance production at large x and so is further limited to $x \lesssim 0.5$. It should be noted that there are still resonance contributions below these limits which are not accounted for in the model.[12]

Finally, since we fit differential and not p_T-integrated cross sections, the six normalization parameters b_q^a in (3) and (4) are in principle p_T-dependent. However, we instead use four ratios, $r_d^a = b_d^a/b_u^a$, $r_s^a = b_s^a/b_u^a$ with $a = (\pi, K)$, which are assumed to be p_T-independent. The small differences in the p_T dependences of the reaction channels studied do not significantly affect our results. The values of b_u^a are then obtained assuming one valence u quark per meson:

$$\int_0^1 V_u^a(x)\frac{dx}{x} = 1. \tag{7}$$

For our final results we also evaluate the structure function first moments

$$\tilde{x}_u^a = \int_0^1 x V_u^a(x)\frac{dx}{x}, \quad \tilde{x}_{d,s}^a = \int_0^1 x S_{d,s}^a(x)\frac{dx}{x}, \tag{8}$$

which give the average momentum fraction carried by each type of quark. The values of $\tilde{x}_q^a$ are linearly related to the coefficients, b_q^a, but are not highly correlated in the fit with the powers, n_q^a.

The parameters n,b, and $\tilde{x}$ obtained from the fit to all our data are given in Table II. The fit has a χ^2 of 251 for 206 degrees of freedom. As an example of the quality of the fit, Figure 1 shows the model predictions (solid curves) together with the $p_T = 0.3$ GeV/c data taken at 100 GeV/c incident momentum. The model describes the data well, but it should be remembered that the model contains six free structure functions corresponding to the six independent reaction channels. By integrating the p_T dependence of the data we also determine the normalization parameters, σ_{inel}^a, in (1). The values obtained are $\sigma_{inel}^{\pi} = 20 \pm 5$ mb and $\sigma_{inel}^{K} = 13 \pm 4$ mb, which are both in reasonable agreement with measured inelastic total cross sections.

The fitted structure functions are displayed in Figure 2. As expected, the valence functions fall less steeply with x than the sea functions. Our pion valence function compares well with the results of an experiment studying pion-produced muon pairs,[13] which are shown by the points with error bars in Figure 2a. The value, $n_u^{\pi} = 1$, is also in agreement with other experimental results [14] and theoretical predictions.[2,15] In particular, quark counting rules would predict $n = (2\, n_{spec}-1) = 1$, where n_{spec} is the number of spectator, or left-over, quarks.[16] The indication that the kaon valence function has $n_u^K = 2.5$, and is therefore steeper than the pion one, is a new result. However, as pointed out earlier, the (1-x) power for the strange valence quark of the kaon is expected to be $(m_u/m_s)n_u^K$, or approximately 1.5, which is closer to the pion result. Finally, it should be recalled that the valence powers are determined in the recombination model not only from the function V_u^a for the incoming meson, but also from R^c as given in (5) for the outgoing meson.

The value $n_d \simeq 3.5$ for both the non-strange sea functions is also in reasonable agreement with the counting rules, which would predict either 5 or 3 depending on whether one counts valence and sea spectators, or only valence spectators.[17] It is interesting to note that the strange sea function for the pion is less steep than the non-strange one, although the integral of the strange sea function is an order of magnitude smaller. This may be the result of the effective mass difference between these quarks. The kaon strange sea is poorly determined because of the sparse statistics for the $K^{\pm} \rightarrow K^{\mp}$ channel.

As in the case of the recombination model analysis of proton-induced reactions,[4] the sea quarks appear to carry a large fraction of the incident meson's momentum. The total momentum fraction carried by the quarks in the pion is

$$\tilde{x}_{tot}^{\pi} = 2\tilde{x}_u^{\pi} + 4\tilde{x}_d^{\pi} + 2\tilde{x}_s^{\pi}, \tag{9}$$

where $\tilde{x}_u^{\pi}$ refers only to the valence quarks. A similar relation holds for kaons which takes into account the somewhat larger value of $\tilde{x}$ for the strange valence quark. Using the results in Table II we then get $\tilde{x}^{\pi}_{tot} = 1.2 \pm 0.1$ and $\tilde{x}^{K}_{tot} = 1.0 \pm 0.1$. The saturation of the sum rule (9) by the quarks thus suggests that a "turbulent" sea accounts for the momentum usually carried by gluons. It is important to note that in addition to the fitted errors for $\tilde{x}^{a}_{q}$ shown in Table II, there is overall normalization uncertainty resulting from the use of the condition (7) together with the function V^{a}_{u} given in (3). Our data are insensitive to the small x behavior of V^{a}_{u}, whereas the assumed factor of $\sqrt{x}$ has a strong influence on the integral in (7). For example, if V^{a}_{u} were instead parameterized as $x(1-x)^{n}$, the values of n and the relative values of $\tilde{x}$ would not be significantly affected, but all values of $\tilde{x}$ would be approximately 40% lower.

We have also tried many variations of the recombination model fit discussed above. For example, extending the x range of the fit does not significantly change the results. Fitting the positive and negative beam data independently gives results similar to those in Table II, except that the normalization of V^{π}_{u} is about three standard deviations higher (lower) for the $\pi^{+}(\pi^{-})$ data. The dashed curves in Figure 2 show the positive and negative beam fits to the $\pi \to K$ channels; the difference between these curves and the composite fit gives rise to the V^{π}_{u} difference. Finally, we have reparameterized F^{a}_{u} as a single function,

$$F^{a}_{u_{eff}}(x) = b^{a}_{u_{eff}}(1 - x)^{n^{a}_{u_{eff}}}, \tag{10}$$

instead of $V_u^a + S_d^a$. The resulting sea quark distributions are unchanged, and the fitted parameters of $F^a_{u_{eff}}$ are included in Table II. We see that $n^a_{u_{eff}} = n^a_u$, and that $\tilde{x}^a_{u_{eff}} = \tilde{x}^a_u + \tilde{x}^a_d$, as would be expected.

In conclusion, within the framework of the recombination model we have extracted information on the pion and kaon structure functions from our low p_T inclusive scattering data. The pion valence function is in agreement with previous determinations, while the kaon non-strange valence quark distribution behaves like $(1-x)^{2.5}$. The non-strange sea quarks have a $(1-x)^{3.5}$ behavior for both the pion and kaon, and appear to carry most of the momentum of the fragmenting meson. The results also suggest that the pion's strange sea quarks have a flatter x distribution than the more abundant non-strange ones.

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TABLE I

Reaction	F_q^a	$F_{\bar{q}}^a$
$\pi^\pm \to K^\pm$	$V_u^\pi + S_d^\pi$	S_s^π
$\pi^\pm \to K^\mp$	S_s^π	S_d^π
$\pi^\pm \to \pi^\mp$	S_d^π	S_d^π
$K^\pm \to \pi^\pm$	$V_u^K + S_d^K$	S_d^K
$K^\pm \to \pi^\mp$	S_d^K	S_d^K
$K^\pm \to K^\mp$	S_s^K	S_d^K

TABLE II

Function	n	b	$\tilde{x}$
V_u^π	1.0 ± 0.1	0.75 ± .01	0.20 ± .01
S_d^π	3.5 ± 0.2	0.82 ± .08	0.18 ± .02
S_s^π	2.2 ± 0.2	0.07 ± .01	0.02 ± .01
V_u^K	2.5 ± 0.6	1.02 ± .04	0.12 ± .02
S_d^K	3.6 ± 0.3	0.71 ± .21	0.15 ± .02
S_s^K	7.5 ± 2.6	0.47 ± .27	0.05 ± .02
$F^\pi_{u_{eff}}$	1.2 ± 0.2	0.71 ± .07	0.32 ± .02
$F^K_{u_{eff}}$	2.6 ± 0.3	1.02 ± .10	0.28 ± .02

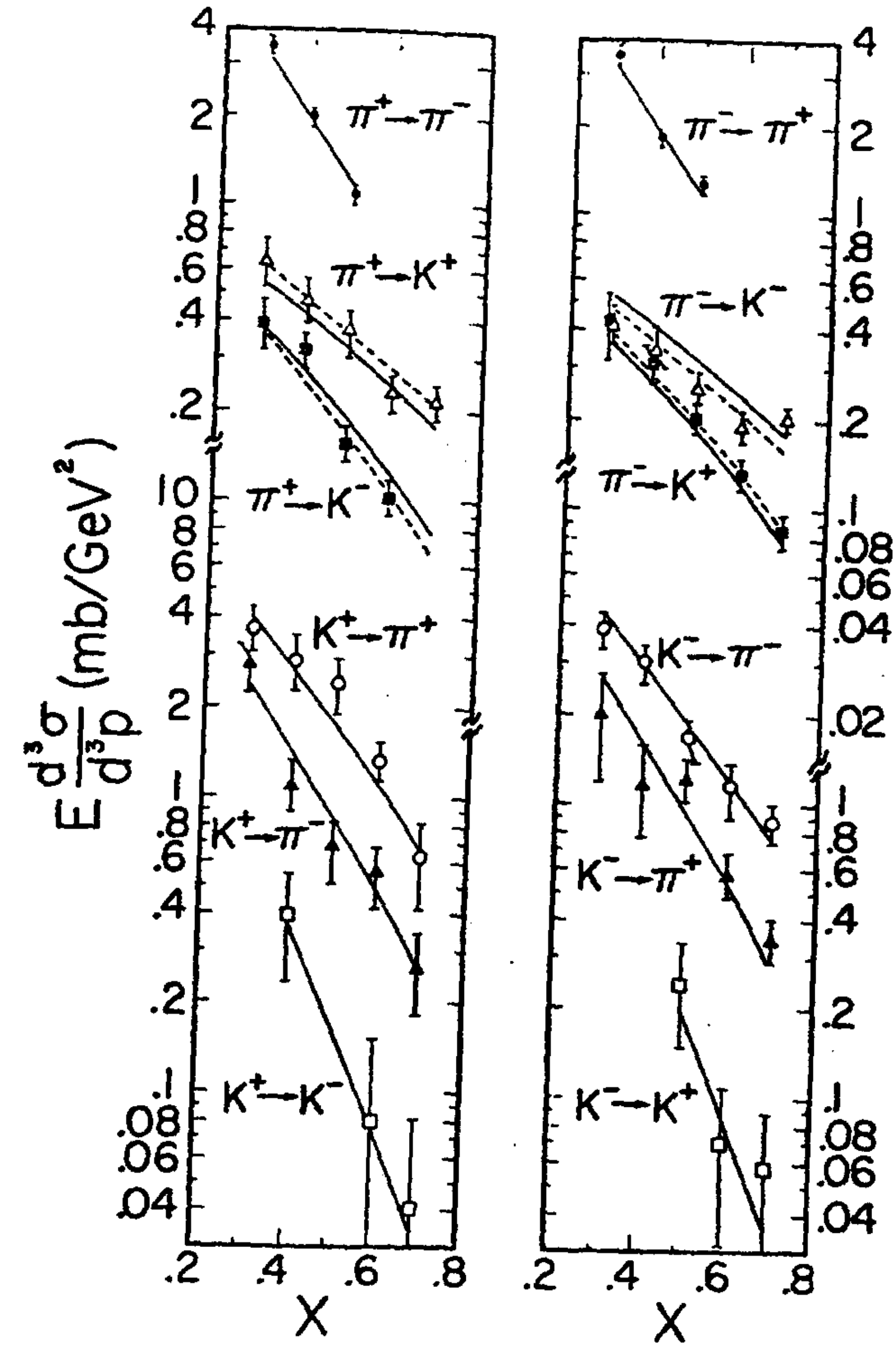

Fig. 1. Invariant cross sections plotted vs. x for the reactions $a + p \to c + X$ at $p_T = 0.3$ GeV/c and $p_{BEAM} = 100$ GeV/c. The recombination model fit to all the data is shown by the solid curves. The dashed curves represent separate fits to the positive and negative beam data where they differ from the composite fit.

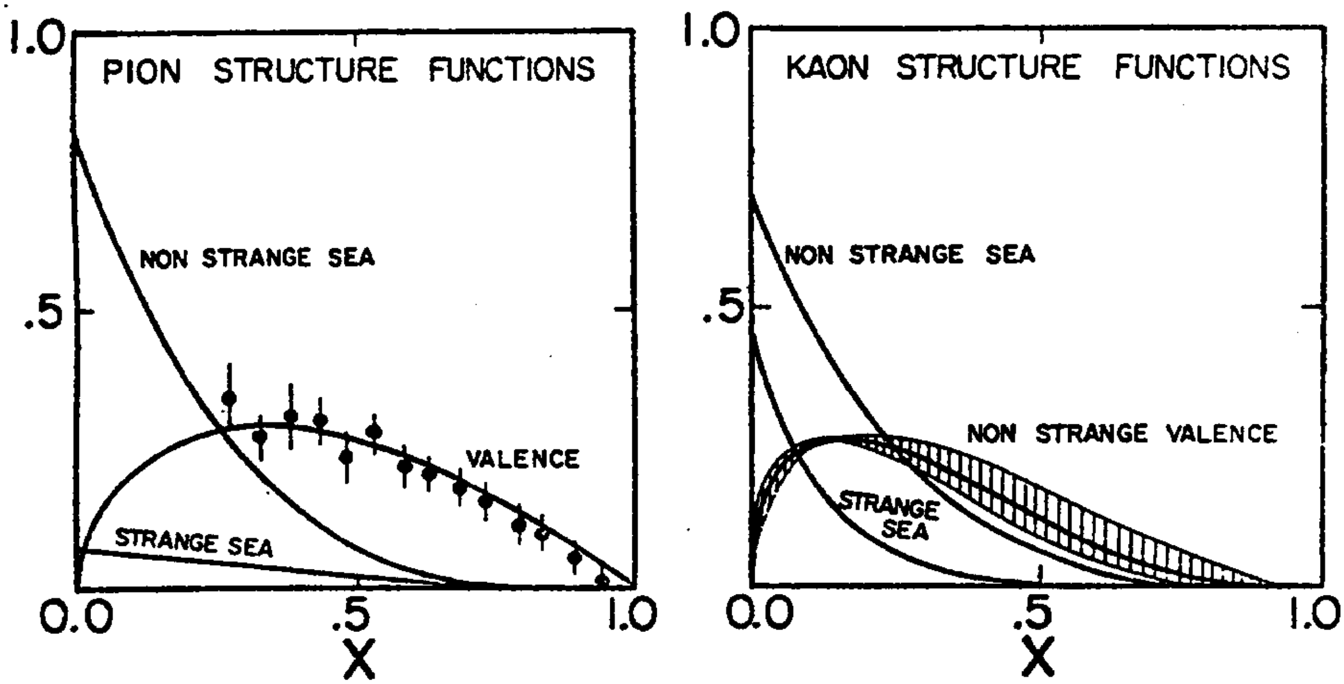

Fig. 2. Pion and kaon structure functions obtained from the recombination model fit. The data points for the pion valence function are from Ref. 13. A typical one standard deviation error band is shown for the kaon valence function.